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Spectrum Sharing and Cognitive Radio

Opportunities for Efficiency Enhancement

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Abstract—Spectrum sharing has been the subject of a 3 year research programme organised by the UK's Virtual Centre of Excellence in Mobile and Personal Communications. Cognitive radio was identified as a key enabling technology to allow spectrum to be shared efficiently between terminals and networks. The project has harnessed the skills of 4 UK Universities working together to understand the potential benefits for its industrial members of cognitive radio technology. This paper discusses some of the work that has been carried out by the Mobile VCE researchers in the field of cognitive radio together with some of the key results and conclusions. The central work has developed algorithms that control the dynamic allocation of radio resources between cooperating network operators as well as spectrum access protocols that allow suitably equipped terminals to sense and use free spectrum. Simulation work has shown that a gain in the efficiency of spectrum use is feasible for both types of spectrum sharing.

Keywords—component; cognitive radio; spectrum sharing; spectrum sensing

I. INTRODUCTION

Cognitive Radio (CR) has emerged in the last few years as a promising research area, due to its potential to improve the efficiency of radio spectrum usage and enhance wireless service. Proponents of CR have predicted that the wireless devices of the future will be unencumbered by the notions of spectrum allocation and network architectures, and will instead comprise of super-intelligent terminals able to self-organise in such a manner as to provide highly efficient communications on demand, understanding the needs of their users. It's not hard to understand why many researchers have been attracted to the topic with its appealing mix of advanced wireless technology and the possibility for massive increases of efficiency in spectrum usage.

To that end, the CR field has seen a flurry of academic activity over the last few years. The work is now gaining ground in the application arena, such that standardisation

activities are underway [1] and regulators are also considering the implications [2].

A. Mobile VCE

The United Kingdom's Virtual Centre of Excellence in Mobile and Personal Communications (Mobile VCE) brings together a number of UK universities to conduct research funded and guided by 15 leading telecommunications companies. This strong combination of academic and industrial partners provides a unique environment to ensure high quality, industrially relevant research.

Mobile VCE has made CR one of the foci of its 3 year Core 4 programme (2006-2009), as part of a wider activity on the abilities of innovative radio techniques to provide an increase in efficiency and a fall in the cost of transmission per bit. Spectrum Sharing (SS) is seen as one possible approach to improving efficiency; intelligent techniques and increased collaboration between networks and terminals are expected to yield benefits in the usage of spectrum.

CR has been identified as a possible enabling technique to supply the functionality necessary to achieve flexible and intelligent usage of spectrum, according to the needs of users thus maximizing the opportunities offered by the radio environment.

B. Key Research Topics

A task of the Mobile VCE programme was to establish to what extent CR could prove to be an enabler for improved spectrum usage efficiency and in which particular types of deployment (considering network architecture, user distribution etc) its benefits could be best exploited.

An initial study of the literature [3], combined with the insight of the needs of the Mobile VCE industrial members highlighted a number of questions and implementation challenges that had not been well addressed by previous work. These included:

- How spectrum can be shared in near real-time between co-operating network operators, taking advantage of different traffic loading requirements to

ensure that commonly managed radio resources are used to maximise efficiency.

- How idle spectrum can be identified and used on an ad hoc basis where the locations and types of spectrum are changing in a highly dynamic manner.
- How reliably can instantaneous spectrum occupancy be measured and what methods exist to improve detection reliability.
- How idle spectrum can be re-used for relaying, within the cell of a cellular network.
- How interference mitigation and co-operative transmission techniques using antenna arrays can be incorporated to allow two (or more) users simultaneously to share the spectrum.
- How the requirements for implementation of dynamic spectrum sharing will require new hardware RF techniques.

The portion of the work presented in this paper covers the first three points, encompassing the development of network algorithms to support SS, studies of networks using these algorithms and investigations of supporting techniques. Assessment has been undertaken using both analytical techniques as well as simulation. The aim to consider the overall benefits of spectrum sharing, was balanced with an appreciation of the drawbacks that spectrum sharing might incur, in particular the extra complexity and the need for additional over the air signalling.

C. Spectrum Sharing

Spectrum Sharing (SS) as considered by this programme covers both opportunistic sharing, (e.g. sensing of and transmission in spectrum white space) as well as managed sharing of radio resources between multiple operators. The opportunistic sharing is CR in its most common definition.

The concept of SS used throughout the work implies that a portion of spectrum normally allocated to a particular user or network can be temporarily used by a different user or network. This is achieved in two main ways; by reassigning allocated spectrum on a short-term basis or by making opportunistic use of available spectrum. The first method is applicable where the licence holders of one or more cellular networks agree to implement sharing. The second method implies that the users' terminals are themselves able to identify which portions of spectrum are free and then use them as required. These latter abilities are aligned with the concept of CR, which proposes that radio terminals can be enabled to learn about their operating environment and then alter their transmission parameters in order to optimise both their own and their network's performance.

D. Organisation of this Paper

Section II considers the operation of managed spectrum sharing which, for this project, has demonstrated the benefits of two network operators sharing the allocation of radio resources between themselves on a real time basis, according to actual and predicted traffic demand.

Section III concentrates on the opportunistic exploitation of spectrum white space, which may exist in licensed bands

due to the temporal and spatial traffic patterns of the primary users.

Section IV considers the detection of free spectrum, in particular the improvement in sensing accuracy by forming nodes into teams. Finally, Section V has some overall conclusions from the work.

II. MANAGED SPECTRUM SHARING

1) Introduction

This part of the project has investigated spectrum sharing between different networks using the same type of Radio Access Technology (RAT). Sharing takes advantage of uncorrelated temporal-spatial characteristics of spectrum usage between two or more Radio Access Networks (RAN), such that radio resources can be shared between cellular operators. Two major types of spectrum sharing are considered; Dynamic Spectrum Allocation (DSA) is used when sharing is controlled by collaborating network operators and Dynamic Spectrum Selection (DSS) where the sharing is implemented by the User Equipment (UE) negotiating access with a number of networks. The focus of this work is to develop protocols for effective resource sharing between cellular operators using Universal Mobile Telecommunication System (UMTS). The intelligent protocols developed achieve this by anticipating the demand for radio resource based on predictions of traffic models.

2) Dynamic Spectrum Allocation

The scenario considered for SS using DSA comprises multiple operators who have rights to a number of radio carriers. The operators are able to temporarily allocate resources on one of their own carriers to a user associated with a different network.

To facilitate spectrum sharing between operators, collaboration is implemented at a network level. The sharing of Radio Network Controller (RNC) minimizes delays and signalling between the operators. It also implies that spectrum sharing can happen on a very fast time scale (order of milliseconds). The mechanism and required architecture is described in [4].

Two cases have been considered "non-pool" and "pool". In the first case, an operator has spare capacity that can be temporarily assigned to a capacity limited secondary system. It is assumed that both operators cover the same geographical area. The second case has a common pool of spectrum, neither operator having prioritised access.

a) Results

Algorithms have been developed [5] to simulate the performance of the protocols that would be incorporated into networks using DSA. These control the allocation of resources to users on the radio bearers of each network. Key simulation parameters are given in Table I.

The results of the simulations for the non-pool case are presented in Fig. 1, for the case where comparison with a convention Fixed Spectrum Allocation (FSA) is made. The horizontal axis in Fig.1 represents the average arrival rate i.e. the system load per cell. The vertical axis represents the Quality of Service (QoS) that defines the level of satisfaction received by the users in the system. The QoS is the

probability that a user is neither blocked nor dropped, as defined in (1).

$$QoS = \frac{\text{Arrived Calls} - \text{Blocked Calls} - \text{Dropped Calls}}{\text{Arrived Calls}} \quad (1)$$

TABLE I. MANAGED SS SIMULATION PARAMETERS

Parameters	Values
Service type	Speech traffic
Data rate	12.2 Kbps
Call Duration	Mean = 120 seconds (Exponential)
E_b/N_0	7 dB
Adjacent Channel Interference	2 %
Soft handover Gain	3
Cell radius	1 Km
Voice Activity Factor	0.67
UMTS carrier bandwidth	5 MHz
Chip rate	3.84 MCps
Simulation borders	Wraparound mobility of MS at simulation borders
Propagation Model	Path loss model with 4 th order power exponent
User distribution	Uniform (No active hotspots)
Frequency re-use factor	1
Handover	Based on geometric cell boundaries
Total Number of cells	12 (with interference modeling)
Carrier distribution	Primary (3 carriers) , secondary (2 carriers), pool (10MHz)
Cell layout	Hexagonal with omni-directional antenna deployment

The higher the number of mobile users that can be accommodated in a cell, the higher the spectrum efficiency that is achieved. The spectrum sharing gain ($\Delta\eta$) is defined as the increase in the spectrum efficiency of the DSA algorithm over FSA. It is measured in terms of the additional load that is supported by the DSA algorithm above FSA at 98% satisfaction ratio. This value is considered sufficient to give the desired level of QoS in the operator's network. The DSA gain formula is shown in (2).

$$\Delta\eta = \frac{\text{Load}_{\text{DSA}, 98\%} - \text{Load}_{\text{FSA}, 98\%}}{\text{Load}_{\text{FSA}, 98\%}} \quad (2)$$

where $\text{Load}_{\text{DSA}, 98\%}$ is Users/Cell/Hour for DSA at 98% satisfaction ratio and $\text{Load}_{\text{FSA}, 98\%}$ is Users/Cell/Hour for FSA at 98% satisfaction ratio.

It is shown that the gain on the secondary system increases up to a point, when the primary system is no longer able to accommodate the secondary users without blocking/dropping its own users. At this point the secondary system switches to FSA as shown. The results also reveal that significant gains can be achieved with reduced complexity and changes to the existing network infrastructure. Spectrum efficiency gain of up to 11% can be obtained at 98% QoS. This sharing approach does not result in the deterioration of the primary system, as shown in [5].

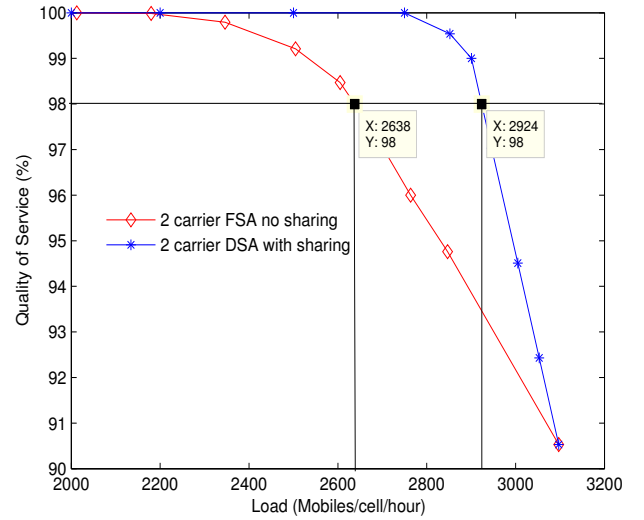


Figure 1. Performance of secondary system performance when sharing with primary

The pool based scheme differs from the non-pool based scenario earlier described since there are no primary and secondary operators. A description of the algorithm is represented in [5]. The key difference from the DSA case is the presence of a load estimation module that predicts the traffic requirements of each of the networks. This is then converted in a code requirement for each RAN. In this case, the temporal variation in the network is exploited to achieve improvements in capacity. The investigation was done for reasonable levels of correlation (80 % to 100 %) between the traffic of the two networks. Specific sets of traffic curves are used in the simulations. At each interval weights corresponding to codes are assigned to the users.

A summary of the results is presented in Fig. 2. The curve shifts to the right as the correlation values changes from 100% to 80%, indicating a capacity improvement above FSA. As shown, the algorithm produces highest gain when correlation is lowest and the gain could be further improved with spatial information. The spectrum sharing gain approaches the suitable theoretic bounds specified in [6].

It is concluded that practical spectrum sharing solutions are possible and significant efficiency gains can be obtained. A gain of 11% was obtained for the non-pool case. Similarly, the pool based case gave a spectrum sharing gain of 4.5%. The efficiency gain due to these two techniques approaches the suitable theoretical bounds described in [6] due to trunking between operators. It can also be seen that the gain is highly dependent on the degree of traffic correlation between the two networks. A high traffic correlation between the two operators results in low spectrum efficiency gains, and vice versa.

3) Dynamic Spectrum Selection

For DSS, the User Equipment (UE) instigates the connection, and so needs to have the ability to detect and communicate with all the existing networks in the area. The call setup and handover procedures need to be modified in a

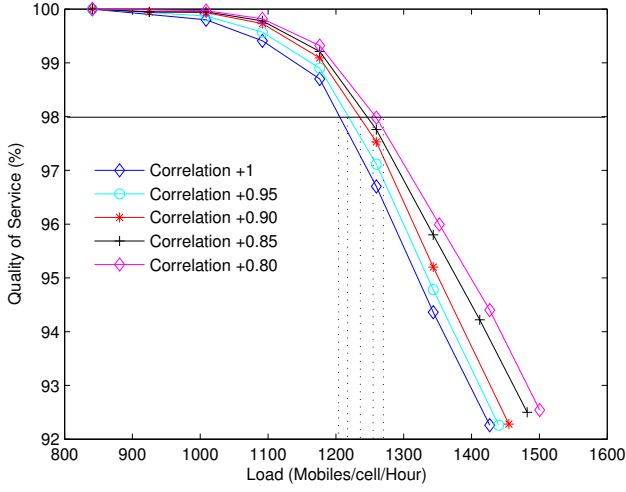


Figure 2. Performance of secondary system with varying traffic correlation with respect to primary system

way that multi-operator functionality can be achieved. Priority of connection requests and users is also an important issue. Each operator desires to maintain QoS of its own users and only shares if extra resources are available. Sacrificing QoS of its own users in order to support a guest user in many cases is not a desirable approach. A “guest user” is the user who originally belongs to another operator and temporarily requests to get service from an alternative operator. Various DSS algorithms can be implemented in a UE for cognitive approach towards efficient management of the spectrum. In this work, an inter-operator DSS protocol is proposed which is based on modified DECT [7].

The proposed protocol is described in [8]. Initially a UE tries to connect to its own network; however upon rejection from its own network the call will not be blocked and other existing networks in the area will also be tested. To elaborate further, in a call setup procedure UE first tunes into the broadcast channel (BCH) of its original network provider and sends a radio resource control (RRC) connection request. If the RRC connection setup is granted, it follows the standard UMTS call setup procedure to set up the call and starts the connection. In the case of rejection it tunes into the BCHs of the other existing networks and sends RRC connection request to them sequentially. It follows this procedure until it gets accepted onto one of the networks or rejected from all.

For the situation where the radio link of a UE is degrading and there are no other links in its active set from the original network, the call can be handed over to another network and inter-operator hand over can take place. In this case UE goes into *compressed* mode and while it maintains its communication with its current network provider it reads the BCHs of other networks and sends RRC connection request to them sequentially. Upon acceptance from one of the operators, inter-operator hand over takes place and the user will be able to continue its call on another network.

Operators can adopt two approaches towards UEs; polite and impolite. In the polite approach if an operator accepts a call it is bound to support the call until it is finished. All the

calls have the same priority upon acceptance into a network and are treated equally. With the impolite approach guest users in a host network have lower priority. This implies that whenever a primary user arrives and there is lack of capacity in the system, the operator drops a guest user in order to support its own user.

a) Results

Fig. 3 shows the network performance using the proposed DSS protocols in the worst case scenario where two networks with the same RATs have entirely correlated average traffic distribution (same capacity demand) during the busy hour. The traffic type is speech; detailed parameters are the same as those used for DSA simulations, presented in Table I. The DSS performance curves are compared with the FSA reference curve. The metric used here is QoS which is calculated according to (3) for voice traffic.

$$QoS = 1 - (P_b + wP_d) \quad (3)$$

Where P_b is the new call blocking probability, P_d is the dropping probability and w is the weighting factor which is considered to be 10 in this work. The spectral efficiency gain metric ($\Delta\eta$) is used to express the increase in spectrum efficiency when comparing the DSS performance to its FSA equivalent and is expressed in (4).

$$\Delta\eta = \frac{T_{DSS}^{98\%} - T_{FSA}^{98\%}}{T_{FSA}^{98\%}} \quad (4)$$

Where $T_{DSS}^{98\%}$ is the throughput achieved by DSS for each cell at 98% QoS measured in kbps/MHz/cell and $T_{FSA}^{98\%}$ is the throughput of the conventional FSA at 98% QoS.

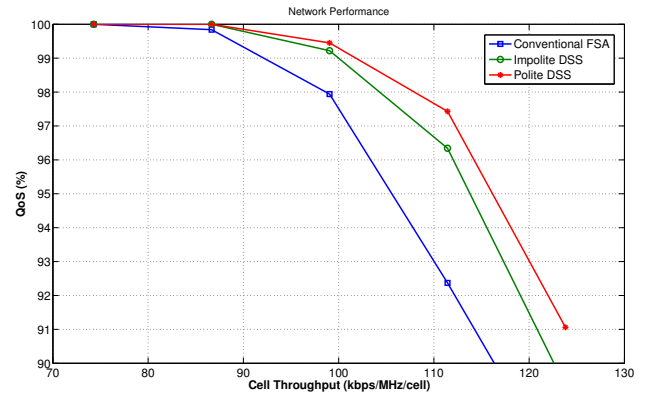


Figure 3. Inter-operator DSS protocol performance on two networks with identical average daily traffic distribution

It can be seen that even in the worst case scenario where two networks have entirely correlated average daily traffic distribution and equal average arrival rate during busy hour, each operator is able to increase its throughput up to 10% due to statistical multiplexing. Based on the investigations [8] the DSS protocols can improve throughput of each cell

up to 25% depending on the protocol which has been used and whether the queuing scheme has been benefited from.

In many schemes, fairness in sharing is one of the concerning issues. For instance if two operators have access to a pool of spectrum, one operator can start using more of that pool by creating false loading information but, in the DSS protocols, opportunities which appear on each network are fairly shared between the users of involved networks and access to an operator's spectrum does not take place unless the operator grants it.

It was also shown that in the situations where the traffic curves are less correlated, higher gains can be achieved and hence better spectrum utilisation can be accomplished. Based on the statistics gathered from the simulator it was revealed that the compressed mode and additional signalling load for call setup and inter-operator handover are not high and do not have considerable effects on the performance of the proposed protocols.

4) Game Theory Analysis

In tandem with the protocol developments and simulation, analytical work on spectrum sharing strategies has focused on the use of game theory [9][10]. This is considered a useful technique to employ, in the light of a sharing system where different resource allocation entities require access to limited spectrum resources.

The players in this game either cooperate in allocating the resources (such as in DSA scenarios), or they compete for the resources, for instance as in an unlicensed band. Spectrum sharing provides an interesting context in investigating the optimum coexistence strategies to reach answers for such crucial questions as whether to collaborate or compete for resources and under which circumstances secondary spectrum access should be allowed.

Consider a two-player Game, sharing a channel with the rate region shown in Fig. 4, where $G_{1,1}=G_{2,2}=1$, $G_{1,2}=G_{2,1}=0.25$, $P_{\max}^1=P_{\max}^2=5W$ and the minimum rate requirements of the primary player $R_{p,\min}^1=0.6$ bit/sec/Hz and requested rate of secondary player $R_{s,\text{req}}^2=0.2$ bit/sec/Hz. The target BER= 10^{-4} is assumed.

Depending on the level of QoS to be guaranteed by the resource allocation algorithm to each player, different power allocations and, hence, different operating points will result. Point *O* is the point where the primary and the secondary player achieve $R_{p,\min}^1$ and $R_{s,\text{req}}^2$, respectively, and is the Nash Equilibrium (NE) of the Cognitive Radio Game with sum power minimisation strategy as discussed in [9]. In this extreme case both the primary and secondary players only maintain their minimum required rate. In order to have positive values for this minimal power allocation, the condition in (5) should hold.

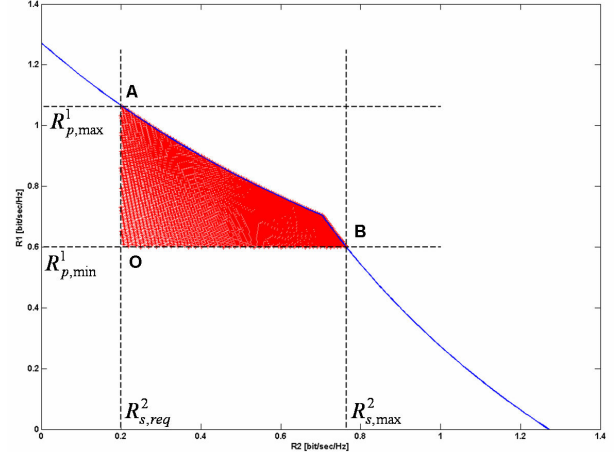


Figure 4. Feasible rate region

$$G_{1,1}G_{2,2} > G_{1,2}G_{2,1} \left(\frac{(2^{R_{p,\min}^1/w} - 1)(2^{R_{s,\text{req}}^2/w} - 1)}{c_3^2} \right) \quad (5)$$

This is an interesting generalization of the similar relations between direct and cross channel gains as reported in [11], and [12], which show that if the mutual interfering effect of two links on each other is low, it is best to share the channel. Equation (5) shows that the same concept is true in the case that a specific QoS level for the primary and secondary system is guaranteed. Therefore, the channel gains and the level of QoS form a trade-off, to decide whether or not to share a sub-channel.

III. OPPORTUNISTIC SPECTRUM SHARING

1) Introduction

Opportunistic sharing is the term used in this paper to describe a system where terminals that collaborate to use spectrum whitespace that may exist on a temporary or long term basis. This whitespace may exist in spectrum ranges that are licensed to a particular user, but become available due to the primary rights holder not requiring permanent use.

In this study, whitespace is exploited by implementing a combination of channel activity measurements and intelligent algorithms in CR terminals. Algorithms to specify the behaviour of individual terminals are key to the CR vision of networks of autonomous nodes that can mutually interact to select free channels whilst avoiding interference to other terminals. A channel selection method has been developed which allows pairs of terminals to communicate on an ad hoc basis by collaboratively selecting a suitable transmission frequency.

The two key challenges that the algorithm solves are that of terminal discovery, which allows neighbouring nodes to locate each other and that of channel selection. These aims are met based on observations of activity on a pool of candidate frequencies; this gives the system elements of cognition, given that it is able to monitor its environment and

make informed decisions about whether to access the spectrum.

2) Channel Monitoring

An algorithm has been developed [13][14], that allows two terminals to select collaboratively a mutually clear channel (i.e. one with the lowest historic levels of activity from other users, both incumbent spectrum users and other similar cognitive terminals). The quality of the channel is assessed by measuring activity on all channels.

Each Cognitive Radio Terminal (CRT) will have a pool of frequencies on which it is capable of transmitting. CRTs monitor the spectrum for packet arrival, thus building up a continually updating picture of spectrum occupancy on each available channel. CRTs will also monitor the presence of “legacy” transmissions, that is to say transmissions from non-cognitive terminals that will not be aware of the presence of the opportunistic system.

As each packet is received, a preference score for the relevant frequency is updated at each receiver; a running score is kept for each of a number of candidate communication frequencies at each CRT. The score for each frequency is adjusted by deducting a fixed amount when a packet is received, and adding a fixed amount when the channel is monitored as silent. If the channel is not monitored, e.g. because the terminal is engaged in another activity, then the score will typically be reduced. Various scoring strategies have been investigated [13], including fixed score adjustments as well as ones proportional to received signal strength (or SNIR). A larger score can be deducted if a legacy transmission is detected, in order to allow a greater amount of protection to these types of transmission. In this way, at each call set up time, each CRT has a preference for each of its possible transmission frequencies. CRTs can be given a cautious approach to channel access by specifying a high deduction for a monitored active channel, and a slow recovery time by specifying a small score addition.

CRTs are only able to monitor directly channels to which their RF front-end happens to be tuned (although they may receive additional occupancy information from other terminals). In order to build up sufficient scores on all pool frequencies, an active scanning algorithm may be implemented, which allows CRTs that are not otherwise engaged to switch scan other pool frequencies.

3) Channel Selection

A handshaking process is used before communications takes place, this takes the form of sending out a formatting beacon packets on the candidate frequencies in turn[14]. This allows the participating nodes to discover one another, share channel scores and rendezvous on the best frequency.

4) Results

The simulation approach used custom software tools to model the interaction of the terminals and their behaviour dependent on the traffic requirements and radio environment. Simulations are performed with 10 terminals being deployed randomly on a 100m x 100m grid. The performance of the algorithm is assessed by testing if the 10 terminals when formed into 5 pairs can individually collaborate to communicate successfully; each pair is therefore in

competition with the other pairs for a free channel. In some cases, legacy transmissions are included, which represent incumbent spectrum users whose transmissions must be protected from interference. Simulations have been carried out for various traffic scenarios and terminal deployments, full details are given in [13].

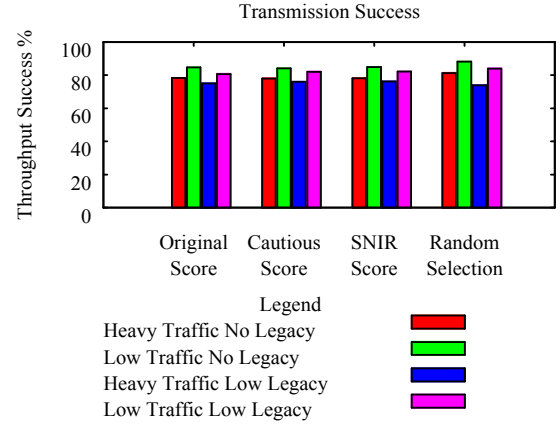


Figure 5. Throughput success

The main statistic that judges the success of the algorithm is the throughput success (i.e. the number of transmitted packets that reach their destination successfully, which is given in Fig. 5 for different combinations of network traffic loading and channel scoring algorithm. Further results are available in [14].

IV. SPECTRUM SENSING

A. Introduction

For cognitive radio applications, the ability of an opportunistic system to sense the existence of other systems; either conformant systems, or other opportunistic systems, is vital. Sensing performance can be characterised by using variables such as the detection probability, $P_{d,i}$ and the false alarm probability, $P_{fa,i}$. An improved detection probability can lead to a higher protection level to primary users while a lower false alarm probability offers better opportunistic access to secondary cognitive nodes. Consequently, a sensing algorithm with higher $P_{d,i}$ and lower $P_{fa,i}$ is desired. This section will present the performance of the proposed algorithms, which include weighted cooperative sensing algorithms, a sensing team selection algorithm and several team node assignment algorithms.

The key contribution of this work has been to increase the effectiveness of sensing by forming CR enabled devices into “teams” that are able to collaborate and decide whether particular channels are occupied. Each CR within the team can be assigned a portion of spectrum to monitor; the team as a whole will therefore build up a picture of spectrum occupancy. Several node teaming algorithms, along with weighted cooperative sensing algorithms have been proposed for cooperative sensing in a mobile case. These algorithms govern:

- The membership of sensing teams (in the time domain) from the set of available CR terminals.
- The frequency band assignment of each member of the teams (in the frequency domain).

These assignments are made by one of the CRs within a team which takes on the role of a sensing coordinator.

B. Simulation Scenario

In order to assess the performance of the team concept, a scenario is considered where an opportunistic communication system must co-exist with a swept radar. It is proposed that CR nodes are able to make use of the spectrum allocated to the radar system when the main transmission lobe is directed away from them.

This scenario is shown in Figure 6. For the team teaming algorithms, the algorithms effectively update the sensing-active team, select and assign the team nodes to perform the sensing task. Combined with using weighted cooperative sensing algorithms, different sensing improvements can be achieved under both two sensing-priority criteria.

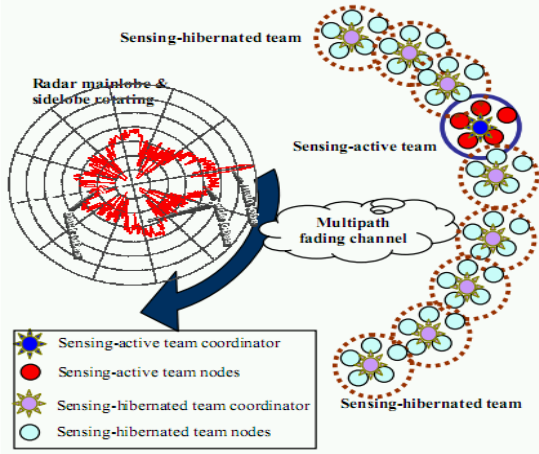


Figure 6. Co-operative sensing scenario

C. Detection Algorithm

The decision about whether the assigned frequency band is occupied is made at the coordinator for each sensing team, based on measurements made by the team members.

To improve the performance of cooperative sensing, several weighted cooperative sensing algorithms are proposed for two criteria (Local Constant False Alarm Rate [LCFAR] and Local Constant Detection Rate [LCDR]). The first criterion is introduced from the perspective of maximizing the opportunistic access for secondary cognitive nodes, in which a local node is assigned a local constant $P_{fa,i}$ to achieve its target detection probability. For the second criterion which offers better protection level to the primary system (radar), the local node tries to achieve a target false alarm probability, constrained in a local $P_{d,i}$.

The weighted decision process is given in Fig. 7. The

channel is sensed as occupied if $\sum_{i=1}^N W_i \times u_i \geq K$, $K = 0$ for

the majority fusion rule. u_0 is the global decision and u_i is the local decision from sensing node i (detector i).

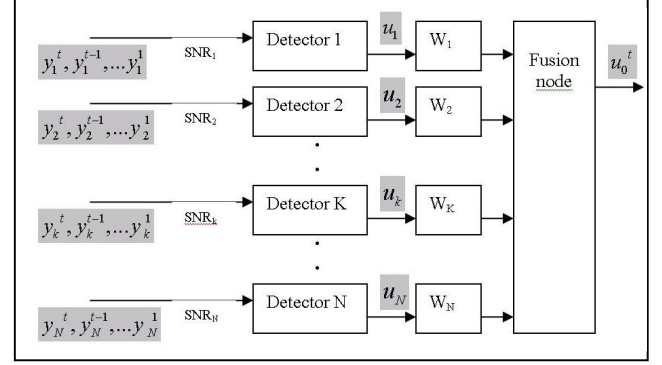


Figure 7. Fusion node

Firstly, an analytical weighted algorithm is proposed as follows, which is based on $P_{d,i}$ -related weights and $P_{fa,i}$ -related weights. Different weighting factors for the nodes are calculated according to the local sensing performance of these nodes. For the criterion of LCDR with a local constant detection probability $P_{d,i}$, the weighting factor W_i for each local sensing node is defined in (6).

$$W_i = 1 - P_{fa,i} \quad (6)$$

Since each node is assigned the same fixed target local detection probability, their local false alarm probability $P_{fa,i}$ is different corresponding to the different SNRs experienced. A node in a higher SNR location has a lower $P_{fa,i}$, in other words, it has a more reliable local sensing performance, therefore its contribution to the global sensing performance is expected to be more significant than those nodes with higher $P_{fa,i}$. In (6), this is considered by increasing the influence of the more creditable nodes with the better sensing performance on the global sensing decision making.

For the criterion of LCFAR with a local constant false alarm probability $P_{fa,i}$, the weighting factor W_i is defined in (7).

$$W_i = P_{d,i} \quad (7)$$

Similar to the criterion of LCDR, those nodes that have a higher local detection probability $P_{d,i}$ will have a more significant contribution to the global sensing decision.

In addition, a SNR_{direct} weighted algorithm is proposed in (8).

$$W_i = Normalized_SNR_i \quad (8)$$

Where the weighting factor $Normalized_SNR_i$ is the linear-normalized SNR value for each node, the basic concept of this algorithm is that the nodes having better SNRs contribute more in the global decision making, and these weighting factors have no relations to the pre-configured target P_{d_i} or P_{fa_i} for each node.

The overall performance of the different sensing algorithms in sensing a pulse radar signal is shown in Fig. 8. The Receiver Operating Characteristic (ROC) curves show the weighted algorithms provide better sensing performance than the standard sensing algorithm in terms of both the global detection probability and the global false alarm probability.

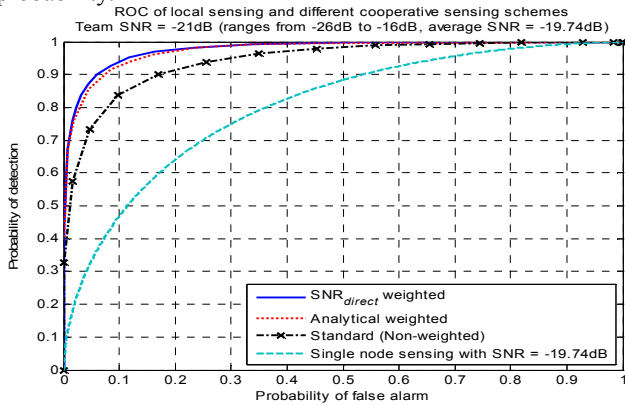


Figure 8. Weighted detection algorithm

V. CONCLUSIONS

The contributions in the field of spectrum sharing that have been made in this programme comprise analysis of the gains in efficiency that can theoretically be achieved using particular implementations of spectrum sharing, as well as the development of techniques and algorithms that show how spectrum sharing could be implemented.

A summary of the techniques investigated which lead to these efficiency gains is as follows:

- The intelligent management of radio resources where two networks co-exist, by using knowledge of the operational conditions of the other network. This knowledge could be obtained through collaboration between the resource allocation mechanisms of the two networks, or could be achieved by permitting one network to monitor the behaviour of the other.
- The detection of unused spectrum and its subsequent re-use for communication purposes. The spectrum may be unused due its allocation to a licence holder which requires less than 100% of their allocation, or may be available for re-use on a temporary basis (e.g. due to traffic patterns with a low duty cycle). Gains due to temporal sharing may also be exploited when the main spectrum occupier has a varying coverage pattern, e.g. a sweeping radar.

Some of the techniques described above require advanced wireless techniques, such as the ability of the

terminal to be aware of its environment (e.g. spectrum usage in its immediate surroundings) and the ability to make decisions based on the awareness. These characteristics are in alignment with a commonly held definition of Cognitive Radio [15]. Work has been undertaken to improve the accuracy of spectrum detection in order to increase the benefits of cognitive radio in spectrum sharing.

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